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THE DESIGN OF A LINEAR, PASSIVE, NONRECIPROCAL, ELECTROACOUSTIC--ETC(U)
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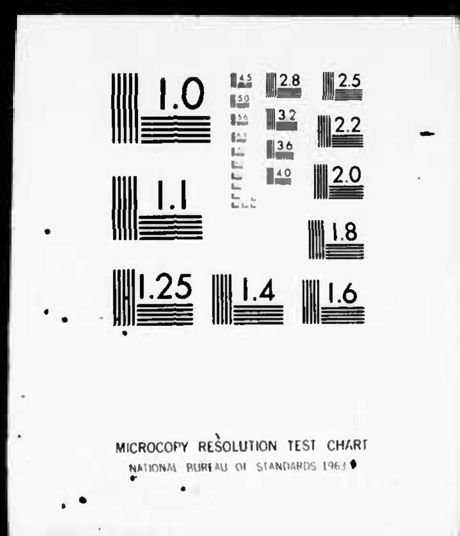

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ABSTRACT

The design of an electroacoustic transducer which is linear and passive, and yet nonreciprocal is described. Emphasis is placed on the design of a particular type of such a transducer because of its possible use in wake homing torpedoes, Leave in ~~by the Navy in wake-homing torpedoes.~~ This transducer has a transmitting-directivity pattern of the single-main-lobe, or searchlight type, and a receiving-directivity pattern of the split-lobe type. ~~twin-lobe, or BDI (Bearing Deviation Indicator) type.~~ This type of nonreciprocity is achieved by combining two different kinds of electroacoustic transducer elements into one instrument. One element must be a condenser or piezoelectric crystal assembly, and the other an electromagnetic or electrodynamic transducer.

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1.0 Introduction

The possibility of designing electromechanical systems that are linear and passive but nonreciprocal was first explained by E. M. McMillan.[1] He pointed out that some types of transducers normally thought of as being reciprocal are, in fact, reciprocal in magnitude but not in phase. By suitably connecting both types of these transducers into a four-terminal network, they can be made to "aid" each other when power is passed through the network in one direction, and to "oppose" each other when power is passed through in the opposite direction, thus forming a nonreciprocal network that is still linear and passive.

¶ The research group at the USRL has succeeded in using the principles explained by McMillan to build a split transducer whose two halves are aiding in transmission and opposing in receiving without any sort of switching. This results in a single-main-lobe transmitting-directivity pattern, and in a split-lobe receiving-directivity pattern. Such a transducer could be used in a Bearing Deviation Indicator system with advantages over present designs, of less or possibly no switching required.

1. E. M. McMillan, J.A.S.A., 18, Oct. 46

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~~using the principles explained by McMillan to build a transducer which performs like the MS4 without any type of switching.~~

2.0 Theory

2.1 Electro-mechano-acoustical Analogies

Consistency in the analysis and definitions used here requires the use of a single type of electromechanical and electroacoustical analogy. For our purposes, it is most convenient to use the analogy:

<u>electrical</u>	<u>mechanical</u>	<u>acoustical</u>
voltage	force	pressure
current	velocity	volume current

2.2 Reciprocal and Antireciprocal Elements

A reciprocal element is defined as an electroacoustic transducer which is reciprocal in both phase and magnitude, or one whose transfer impedances have the same sign. Transducers of the piezoelectric or condenser type are reciprocal elements.

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An antireciprocal element is an electroacoustic transducer which is reciprocal in magnitude only, or one whose transfer impedances have opposite signs. Moving-coil and magnetostriction transducers are of this type.

2.3 Phase Relationships

A reciprocal element is normally an electrostatic device and behaves like a condensor; the mechanical forces involved are in phase with the charge or the voltage.

An antireciprocal element behaves like a wire in a magnetic field where the mechanical forces involved are in phase with the current or 180° out of phase with it, depending on whether we have the case of a generator or motor. We can arbitrarily choose which case gives us the "in-phase" relationship, the important point being only that the two cases differ.

Consider an electroacoustic transducer as a four terminal network with two electrical terminals and two acoustic terminals as shown in Fig. 1.

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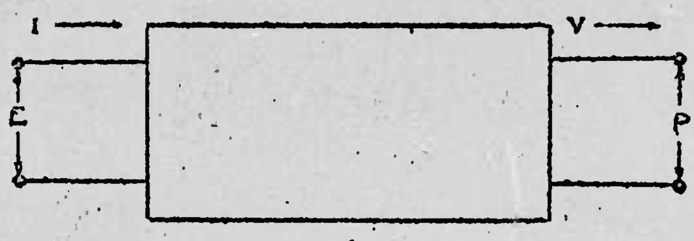

I = current (when V = 0)
E = emf (open circuit)
V = volume current (when I = 0)
P = excess pressure (open circuit)

Figure 1 - Electroacoustic Transducer as Four-Terminal Network

The transfer impedances here are P/I and E/V. For a reciprocal element, P/I = E/V. For an antireciprocal element, P/I = -E/V. For a reciprocal element, the phase between P and I may be unknown, but it is assumed to be the <u>same</u> as the phase between E and V. That is:

if P leads I by an angle θ,

then E leads V by an angle θ.

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For an antireciprocal element, the phase between P and I is assumed to be 180 degrees different from the phase between E and V. That is,

$$\text{if } P \text{ leads } I \text{ by an angle } \theta$$
$$\text{then } E \text{ leads } V \text{ by an angle } \theta + 180^\circ.$$

Now connect a reciprocal and an antireciprocal element in series as shown in Figure 2.

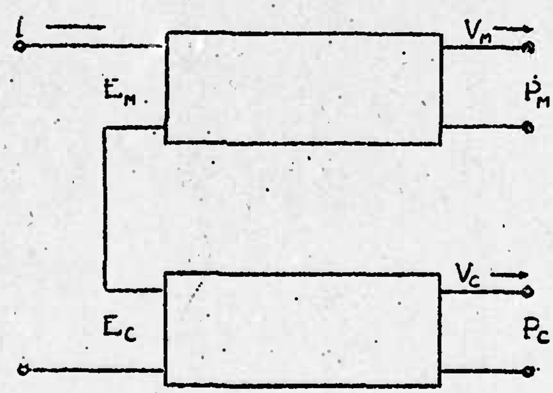

Figure 2 - Reciprocal and Antireciprocal Elements in Series

Assume: P_m leads I by θ_1

P_c leads I by θ_2

Then: E_m leads V_m by $\theta_1 + 180^\circ$

E_c leads V_c by θ_2

When this combination is used as an electroacoustic projector, the sound fields produced at the acoustic faces of the individual elements will be P_m and P_c. Ordinarily P_m and P_c will not be in phase, but will differ by an angle $(\theta_1 - \theta_2)$. A vector representation of this is shown in Fig. 3.

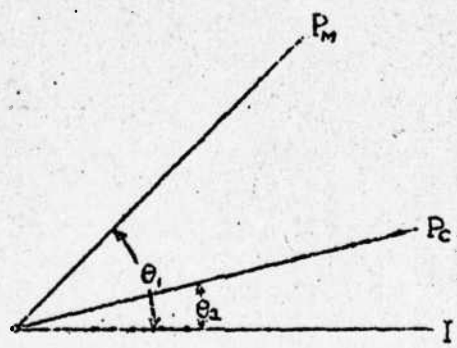

Figure 3 - Phase Relationship Between P_m and P_c.

The direction of maximum constructive interference (i.e., the main lobe) then will not coincide with the mechanical axis of the instrument but will be a function of frequency, of angle $(\theta_1 - \theta_2)$, and of the distance between the acoustic centers of the elements. Call this direction the acoustic axis. See Fig. 4.

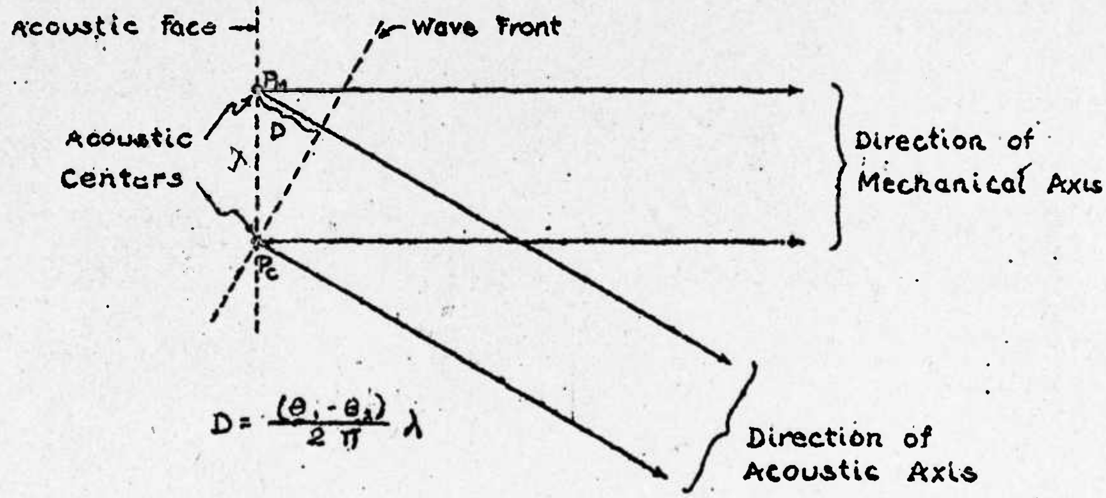

Figure 4 - Direction of Main Lobe of Sound Beam From Combination of Reciprocal and Antireciprocal Transducers Connected in Series

When the combination is used as a hydrophone, with sound being received along the direction of the acoustic axis, the sound fields at the acoustic faces of the individual elements will again have a phase difference of angle $(\theta_1 - \theta_2)$. Now, however, P_c will be leading P_m. Since the phase between P_m and V_m must be the same as the phase between P_c and V_c, we can conclude that V_c will lead V_m by $(\theta_1 - \theta_2)$.

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Thus we have established the following relationships:

V_c $\cancel{V_m}$ leads V_m by $(\theta_1 - \theta_2)$

E_m leads V_m by $\theta_1 + 180°$

E_c leads V_c by θ_2

Therefore, E_m and E_c are 180° out of phase as shown in Figure 5.

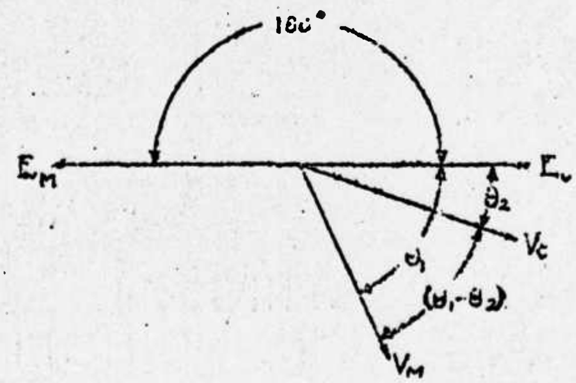

Figure 5 - Phase Relationships Among V_c, V_m, E_e, and E_m.

Inasmuch as the only assumptions regarding the magnitudes and signs of θ_1 and θ_2 made here were for purposes of illustration and drawing the vector diagrams, and since no such assumptions are necessary to reach our conclusion, we have a perfectly general case.

The only assumption made which might be open to question is that which makes the phase between P and I and between

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E and V the same regardless of whether the values are open circuit; that is, whether we work into an infinite load. In practice we do not work into infinite loads, although infinite loads are assumed in defining transfer impedances. In view of our experimental success, the assumption seems to be valid.

2.4 Conditions of Maximum Nonreciprocity

It has been shown that for one given direction, the series combination of two different elements will have a single main lobe pattern on transmission because the two elements produce "aiding" or "in-phase" sound fields. When receiving from this same direction, the two emf's produced will be "opposing" or "out of phase". If the receiving responses of the two elements are now made equal in magnitude, they will cancel each other, and the total receiving response of the combination will be equal to zero. This will appear as the sharp and deep null in a split ~~twin~~-lobe ~~or 2~~ pattern. The transmitting responses will also be equal in magnitude, but they will add up to a total response twice that of either individual element. Under these conditions the maximum nonreciprocity or greatest difference between transmitting and receiving responses is obtained.

2.5 Frequency Limitations

Two factors will limit the satisfactory operation of this instrument to one frequency. Ordinarily the responses of the two elements will be the same for only a few frequencies. Maximum nonreciprocity can possibly be obtained at all these frequencies, but the direction of the acoustic axis will be different for all, since its deviation from the mechanical axis is a function of frequency. In practice, an instrument can usually be mechanically oriented easily; therefore the direction of the acoustic axis is not as important as the fact that it changes with frequency. Even if it were possible to design two different elements whose responses were identical over a wide frequency band, the limitation to one frequency by the shifting acoustic axis would still exist.

3.0 Construction of Experimental Model

3.1 Original Model

The first model, built to test the nonreciprocal theory, was merely an AX70 and an MS4 mounted in juxtaposition on a single rig as shown in Plate 1. The AX70 is an X-cut Rochelle Salt crystal transducer and a reciprocal element. The MS4 is a magnetostriction

transducer and an antireciprocal element. They were connected externally in series.

3.2 Second Model (RL-T2A-1)

After successful tests with the first model, a second model was built by removing half of the magnetostriction units from the MS4 and replacing them with an assembly of Y-cut Rochelle salt crystals. See Plates 2 and 3. The two elements were again connected in series. This first complete and integrated model was designated the RL-T2A-1.

4.0 Test Results

4.1 Original Model Tests

The individual elements of the original model had equal sensitivities at 57.7 kc, and it was at this frequency that the first successful tests were run.. Figure 6 shows the transmitting and receiving directivity patterns with the maxima of one falling at the same angle as the minima of the other. By shunting the AX70 with a low resistance (2 ohms), its sensitivity was matched with that of the MS4 at 25 kc, and the results again were good. See Fig. 7.

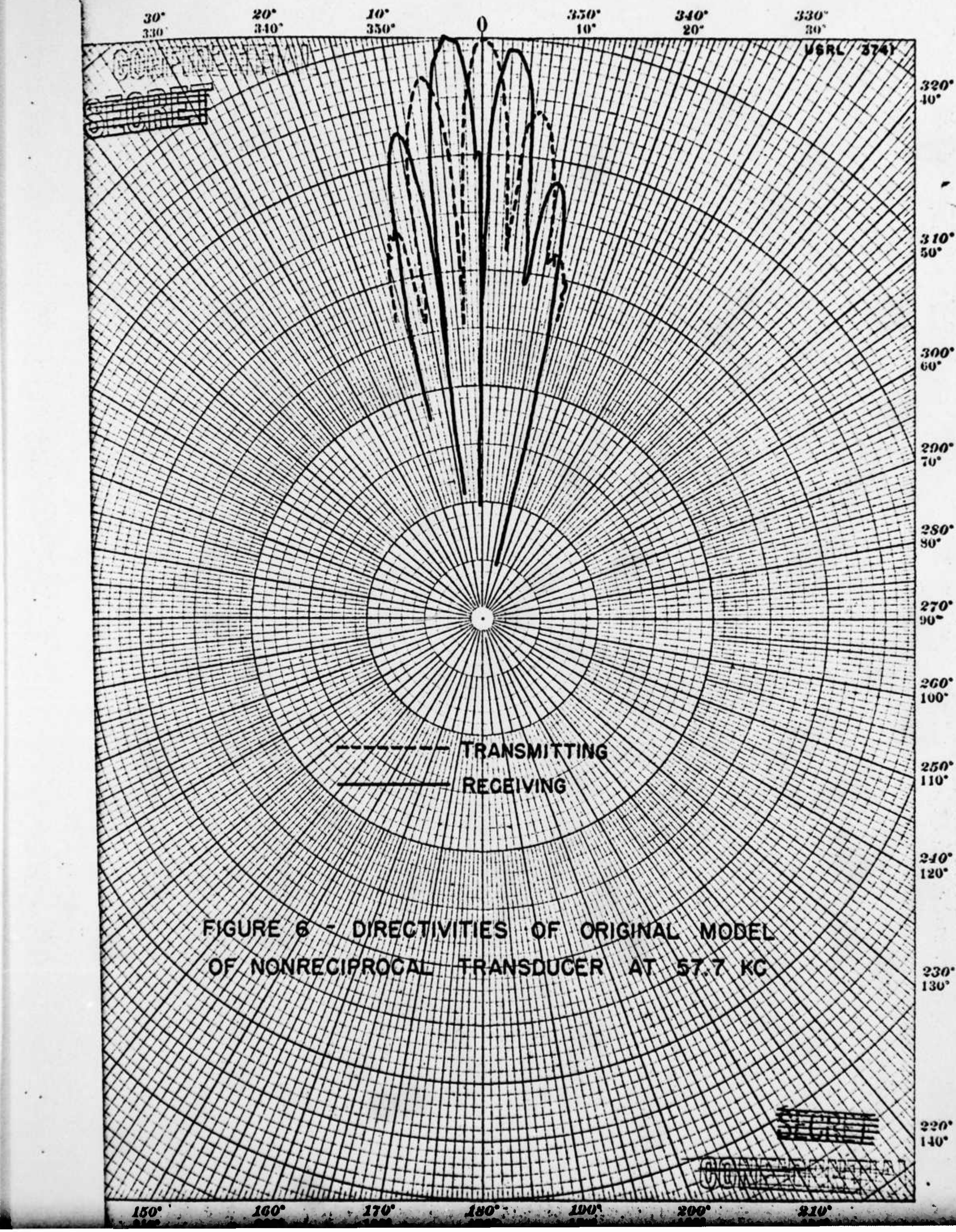

FIGURE 6 - DIRECTIVITIES OF ORIGINAL MODEL OF NONRECIPROCAL TRANSDUCER AT 57.7 KC

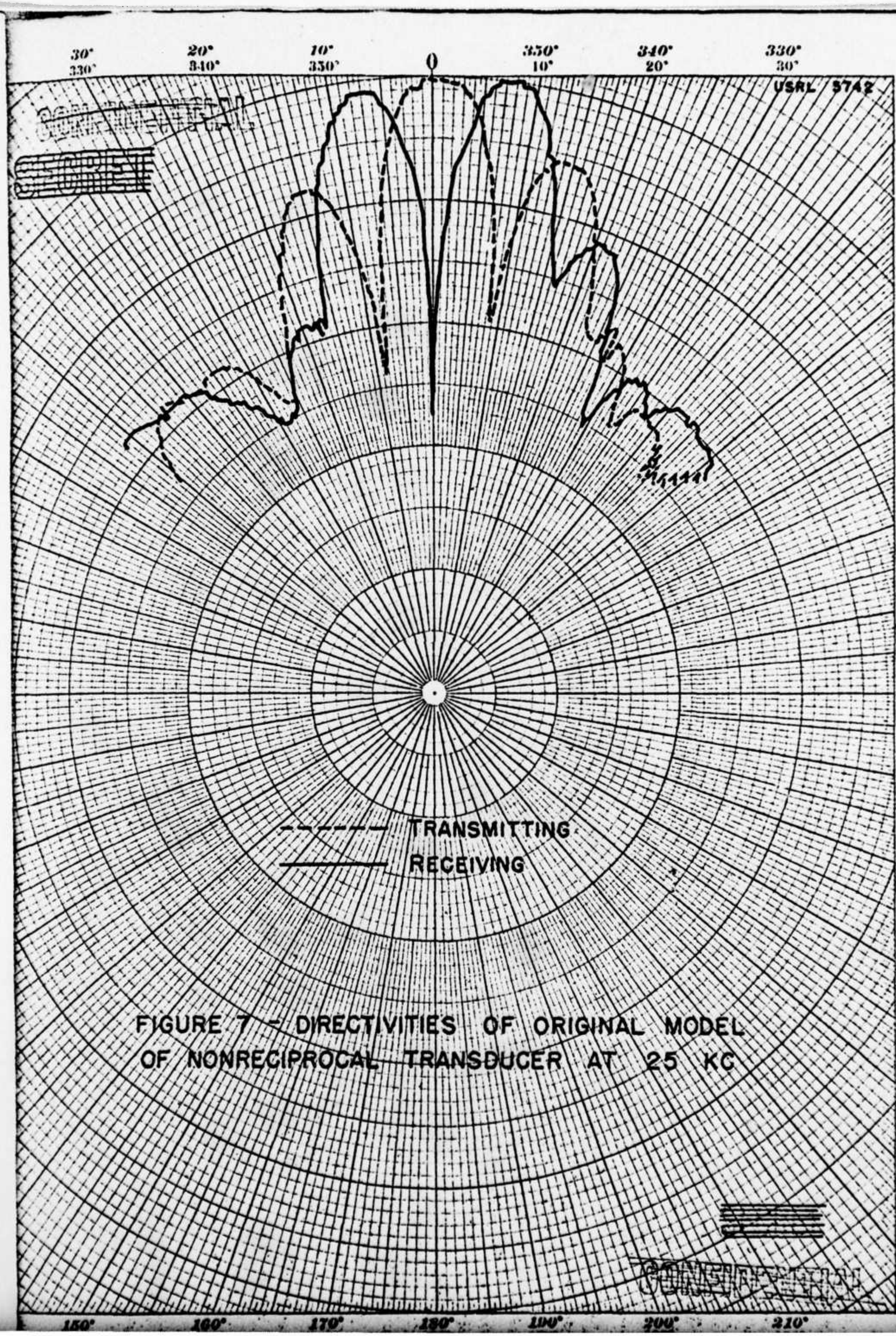

FIGURE 7 – DIRECTIVITIES OF ORIGINAL MODEL OF NONRECIPROCAL TRANSDUCER AT 25 KC

4.2 RL-T2A-1 Tests

The RL-T2A-1 was tested with satisfactory results shown in Fig. 8. By shunting both elements with various impedances, good nonreciprocity could be obtained at many different frequencies and the direction of the acoustic axis could be shifted relative to the mechanical axis.

4.3 Parallel Connections

Connecting the two elements in parallel will also produce nonreciprocal results. However, a parallel connection produces a much lower open-circuit voltage output for the combination than a series connection. Thus the series connection is to be preferred over the parallel.

4.4 Linearity

Tests revealed the RL-T2A-1 to be linear with power.

4.5 Determination of Optimum Frequency.

For a given set of electrical conditions, the instrument will have one optimum frequency at which it will have maximum

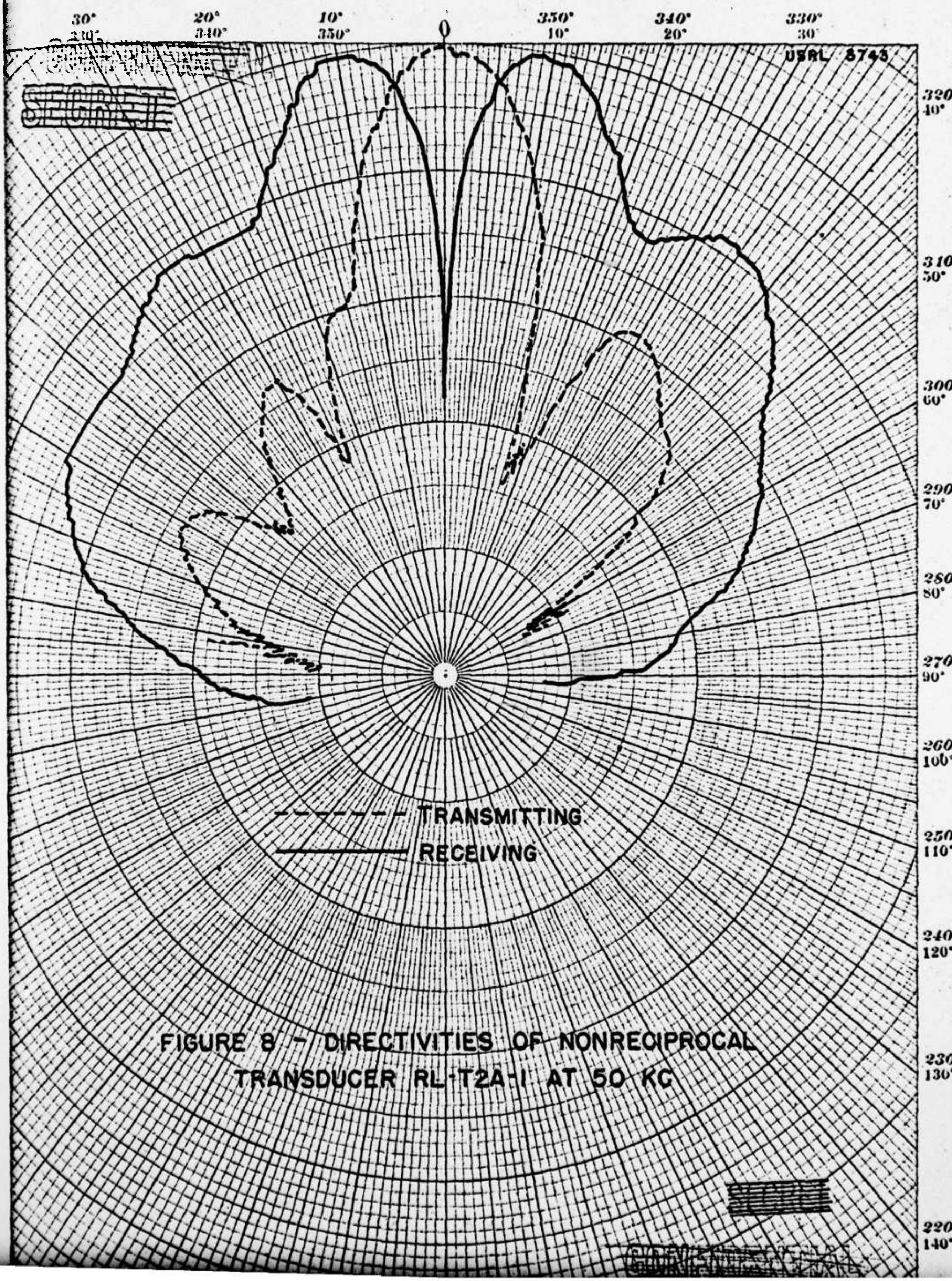

FIGURE 8 - DIRECTIVITIES OF NONRECIPROCAL TRANSDUCER RL-T2A-I AT 50 KC

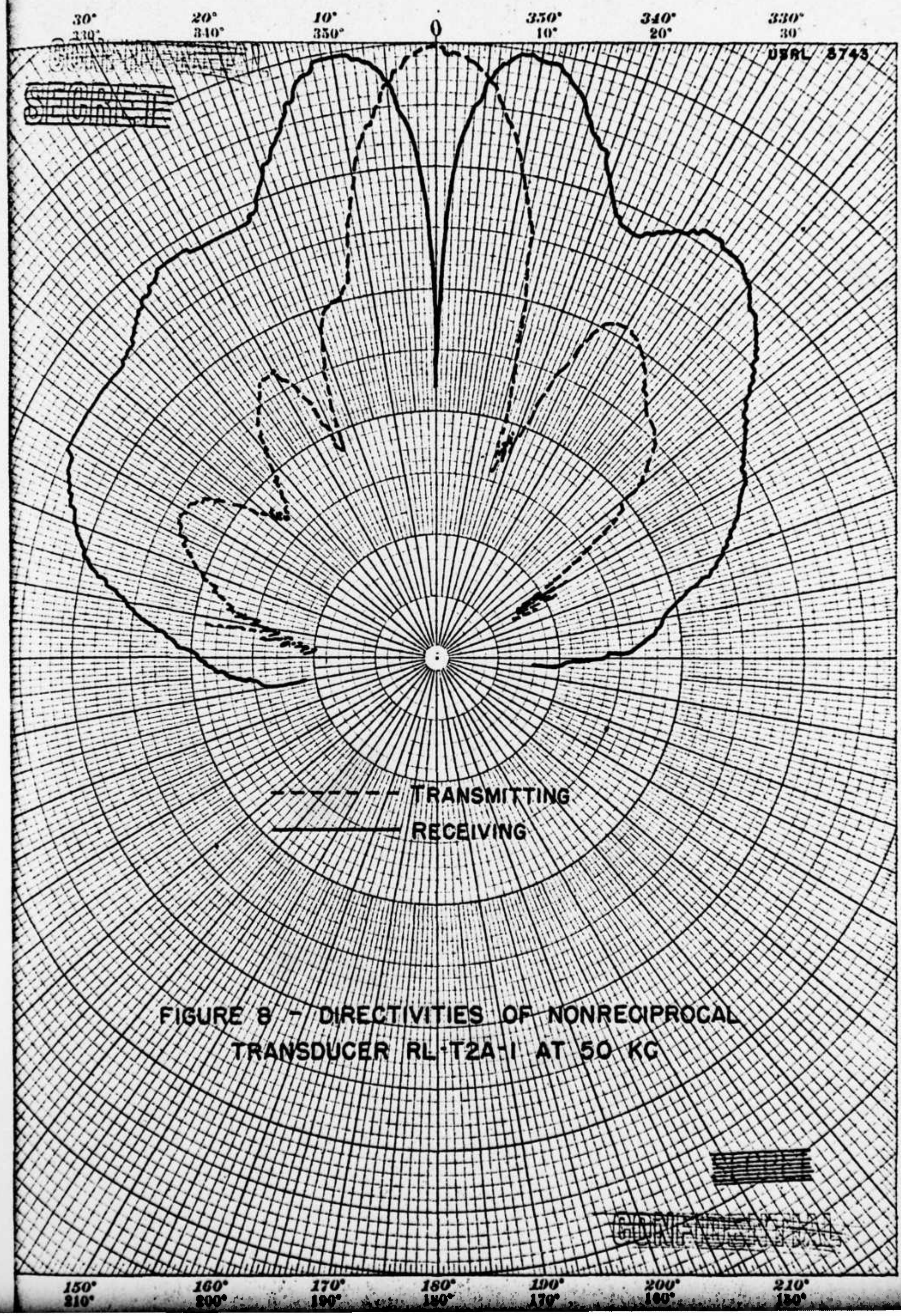

FIGURE 8 - DIRECTIVITIES OF NONRECIPROCAL TRANSDUCER RL-T2A-1 AT 50 KC

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nonreciprocity in one given direction. If a particular optimum frequency is desired, the electrical conditions can usually be changed so as to obtain the desired results. An analysis of the individual element frequency responses will indicate the type of electrical change that should be used to shift the optimum frequency in a desired direction. A frequency response run with automatic recording equipment will reveal the optimum frequency as a sharp minimum in the instrument's receiving response.

4.6 Pattern Reversal

By reversing the electrical leads on one of the two elements, the patterns can be reversed. That is, it will transmit a split-lobe ~~BM~~ pattern and receive a single-main-lobe ~~searchlight~~ pattern.

4.7 Side Lobes

The side lobes in the original model were very high, but further design and development have reduced them. The RL-T2A-1 was an improvement in this direction over the original model.

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5.0 Uses and Applications

Proper design and construction of this typo transducer should make it ideally applicable to the "Sonar Wake Dectotor" [2] and the "Ultrasonic Impedance System" [3] of wake-homing torpedoes. Use of this transducer appears feasible in a bridge-type circuit, and might conocivably avert trouble due to dynamic pressure at high torpedo speeds.

6.0 Conclusion

The tests prove conclusively that linear, passive, nonreciprocal transducers can be built for practical purposes for operation at a single frequency. Multiple combinations of different elements could be used to produce a wide variety of nonreciprocal types.

The theory of operation is, in general, as heretofore outlined. A rigorous analysis of the phase relationships in the electro-mechano-acoustical system remains to be done in detail.

(2) "Sonar Wake Detector", Naval Research Lab., Washington, D. C. Sound Division Report #44. Secret

(3) "Ultrasonic Impedance System" O. R. L. Report from Penn State College. Sept. 15, 1948. Serial No. NOrd 7958-110. Secret.

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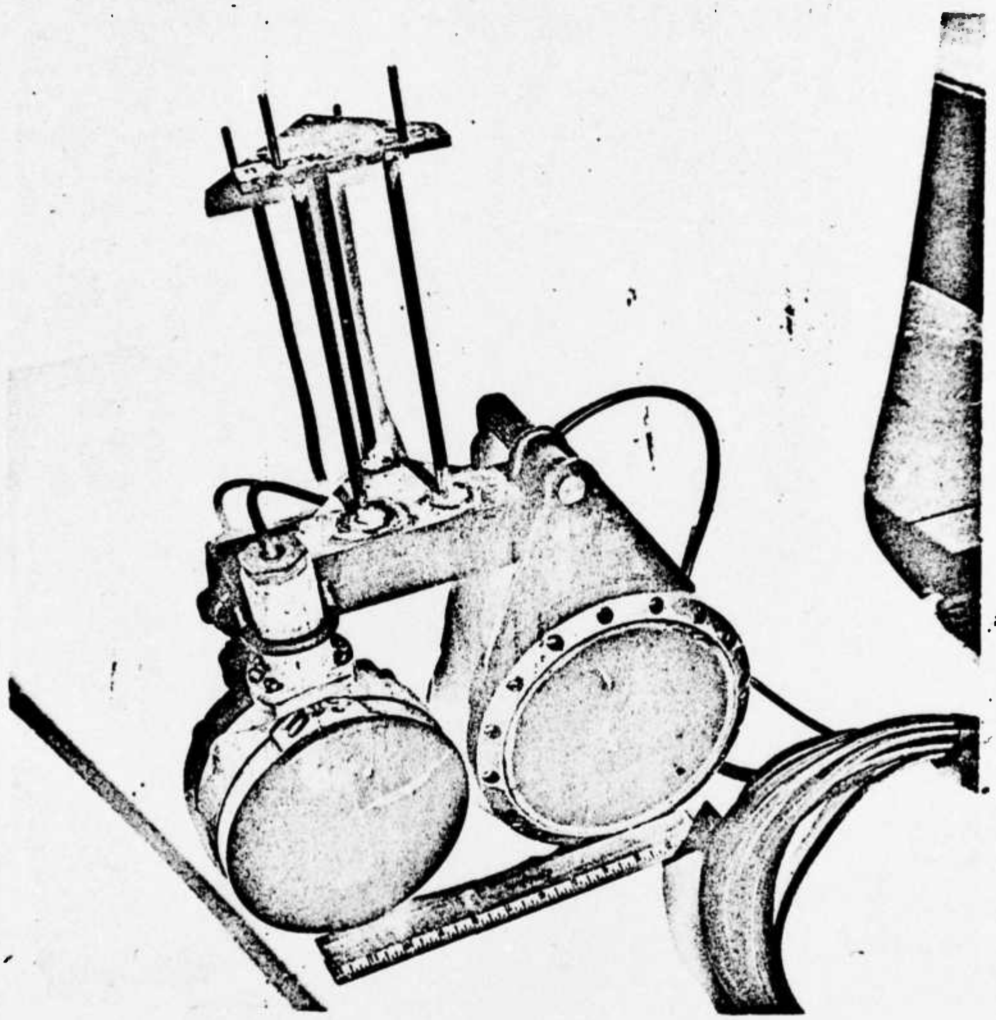

PLATE I. - AX70 and MS4 combination

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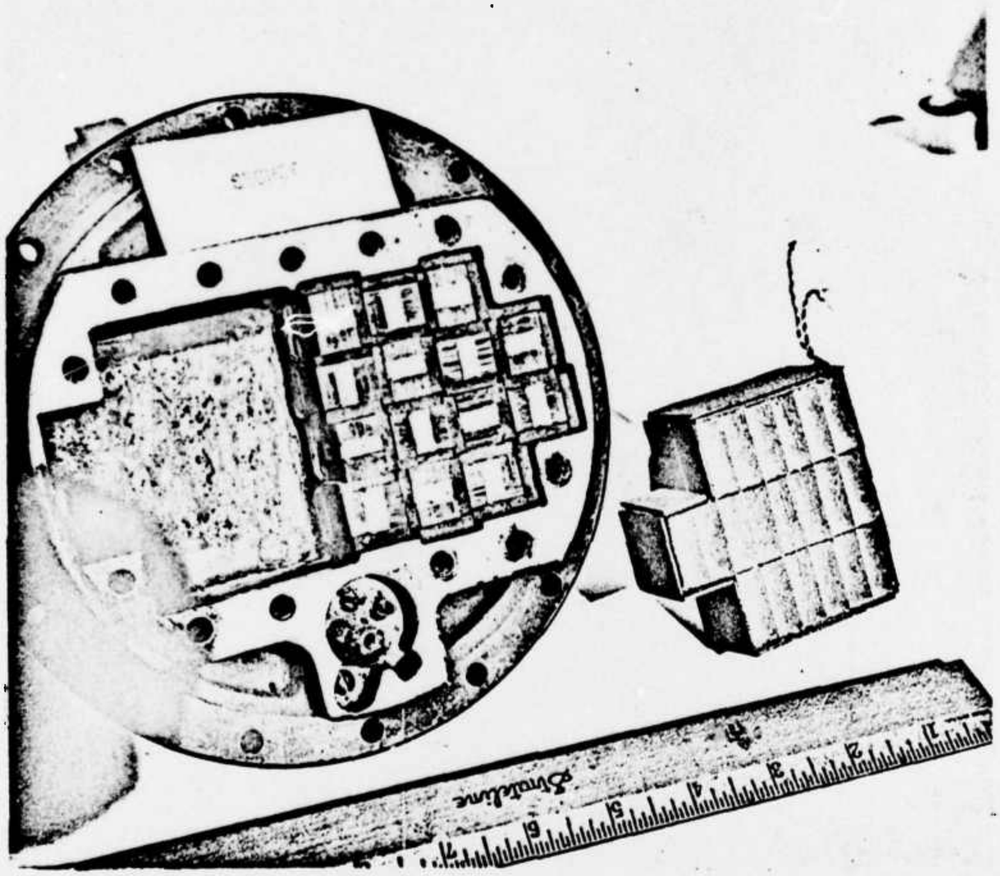

PLATE 2 - Transducer RL-T2A-1
with crystal unit removed

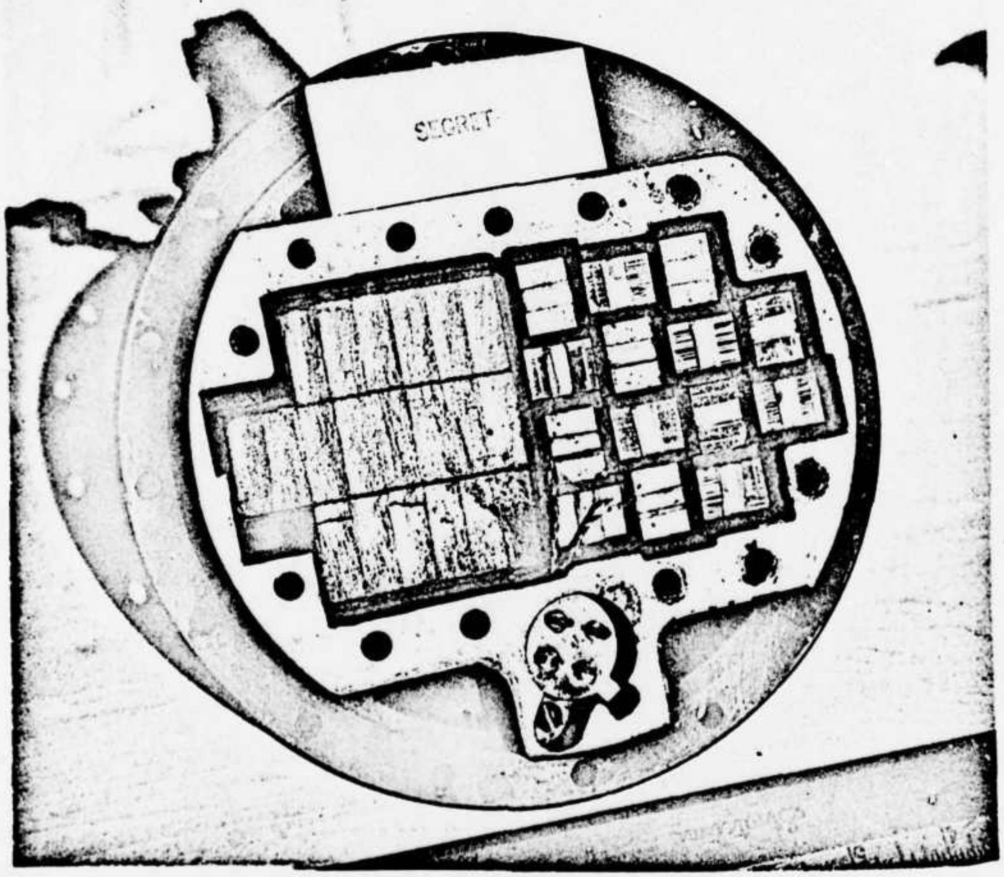

PLATE 3 - Transducer RL-T2A-1

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